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PROPERTY ENHANCEMENT OF SPHEROIDAL GRAPHITE CAST IRON BY HEAT TREATMENT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF

Bachelor of Technology

in

Metallurgical and Materials Engineering

By

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Department of Metallurgical and Materials Engineering
National Institute of Technology
Rourkela

2010

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Under the Guidance of

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Department of Metallurgical and Materials Engineering
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2010

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CERTIFICATE

This is to certify that the thesis entitled, “PROPERTY ENHANCEMENT OF SPHEROIDAL GRAPHITE CAST IRON BY HEAT TREATMENT” submitted by RANJAN MITTAL and SUNIT NANDA in partial fulfillment of the requirements for the award of Bachelor of Technology Degree in Metallurgical and Materials Engineering at the National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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Bachelor of Technology

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ABSTRACT

Ductile iron or popularly known as Spherodized graphite iron (SG iron) is a special variety of cast iron having carbon content more than 3% and has graphite present in compact, spherical shapes. These compact spheroids hamper the continuity of the matrix much less than graphite flakes which results in higher strength and toughness with a structure that resembles gray cast iron, thus imparting superior mechanical properties i.e. much higher than all other cast irons and which can be compared to steels. This unique property enables ductile irons to be used for numerous industrial applications.

Alloying element addition greatly affects the mechanical properties of SG iron with Si, Mn, Cu and Ni being more predominant. While copper helps increasing the tensile strength and hardness causing no embrittlement in the matrix, Ni helps enhancing the U.T.S without affecting the impact test values. Thus addition of Cu and Ni plays an important role in determining the end properties of SG iron after heat treatment.

The high ratio of performance to cost which they offer to the designer and end user makes them to be used extensively for industrial applications. However, to extend the consistency and range of properties of SG iron castings beyond its properties in as-cast condition, Heat treatment is a necessary operation. Tempering and Austempering are the two most widely used heat treatment operations in SG iron. For example a ferritic iron having 70-80% ferrite has a yield strength of 350Mpa while a similar material which is given a step quenching treatment shows a yield strength of 550-1250Mpa. Recently developed Austemperd Ductile iron (ADI) has good abrasion resistance combined with excellent ductility and toughness.

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CHAPTER 1: INTRODUCTION

Spheroidal graphite (SG) cast iron was discovered in the 1948. However,

«lf coke (which is high in sulfur) had not been used for melting iron and if high

purity ores had been used, then ductile iron would have been accepted as the normal

form of iron, with flake graphite iron only being discovered much later as an accident

of adding S and O. This seems to have been close to the situation in China

where spheroidal graphite irons were produced over 2000 years ago [Han91].

» in [Har97]. [1]

The term Cast iron refers to an alloy of iron containing more than 2.0 percentage of carbon. The brittle behavior associated with the cast iron is an outdated and widely held misconception which implies all cast irons are brittle and none of them are ductile in nature. Ductile iron is one form of cast iron which is ductile and it offers the designer a unique combination of high strength, wear resistance, fatigue resistance, toughness and ductility in addition to good castability, machinability and damping properties. Unfortunately these properties of SG iron are not widely well known because of the misconception about its brittle behavior. [2][3][12]

Ductile iron or SG iron was discovered in 1948 at the American Foundry men Society Annual Conference. It was seen that by adding magnesium before pouring caused the graphite to form nodules rather than flakes. This resulted in a new material, with excellent tensile strength and ductility. Adding these mechanical properties of this material to the advantages already offered by cast iron soon led to it finding its way into virtually every mainstream area of engineering, in many cases replacing existing steel castings or forgings due to achievable cost savings. It is shown that, recent process and developments open new avenues to this family of materials.[14]

SG iron is an alloy of iron and carbon having nodules or spheroids of graphite embedded in a ferrite-pearlitic matrix. The nodules are compact spheres and are sharp and regular. The graphite occupies about 10-15% of the total material volume and because graphite has negligible tensile strength, the main effect of its presence is to reduce the effective cross-sectional area, which means that ductile iron has tensile strength, modulus of elasticity and impact strength proportionally lower than that of a carbon steel of otherwise similar matrix structure. The matrix may vary from a soft ductile ferritic structure through a hard and higher strength pearlitic structure to a hard higher and comparatively tough martensitic structure. General engineering grades of ductile iron commonly have the structures which are ferritic, ferritic/pearlitic or pearlitic. Controlled processing of the molten iron precipitates graphite as spheroids rather than flakes. The round shape of the graphite eliminates the material's tendency to crack and helps prevent cracks from spreading. The properties of SG iron are affected by elements like Si, Mn, Cu, Ni etc. Except carbon almost all the elements increase hardness and tensile strength. While except Si, all other elements promotes pearlite, except Si, Cu, Ni all other elements promote carbide formation.[4][10]

Experiments have shown that heat treatment operations can improve the properties of SG iron to such an extent that it may overcome the properties shown by steels. Today austempered ductile iron is considered a bright prospect having a good combination of properties. Combining the tensile strength, ductility, fracture toughness and wear resistance of steel with production of economics of a conventional ductile iron, ADI offers the designer a great opportunity to create superior components at reduced cost. [3]

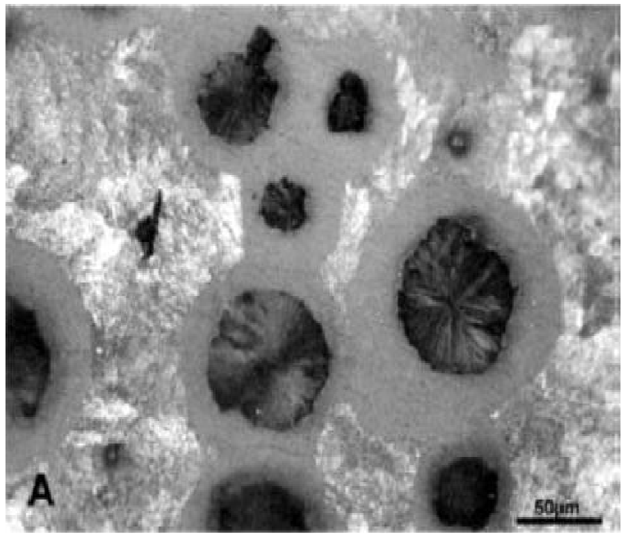

Figure 1.1: SG cast iron in which graphite is in spheroidal form.(Ref 1)

CHAPTER 2: S.G. CAST IRON

2.1 TYPES OF CAST IRONS

Cast irons generally contain more than 2% C and a variety of alloying elements. These are generally classified by a rather simple and archaic system. Classification is done on the basis of the appearance of their fracture surface, their microstructure and properties. There has been two class of cast irons historically, one having a gray fracture appearance and other having a white fracture appearance, named as *gray cast iron* and *white cast iron* respectively. Those irons having both gray and white appearance are called *mottled iron.* It is interesting to note that these names still apply today. Over the years, other cast irons have been evolved which have their name derived from their mechanical property, such as *malleable iron* and *ductile iron*. More recently *compacted graphite iron* and *austempered ductile iron* have been introduced. There are four factors which lead to the different types of cast irons namely, the carbon content, the alloy, the impurity content, the cooling rate and the heat treatment after casting. These parameters control the composition as well as the form of parent matrix phase present.[2][3][14]

Cast irons can be broadly classified into these 5 categories.

1. **Gray cast irons:**

   It is the most common type of cast iron found. It has a gray fracture surface due to high volume of graphite *flakes.* Carbon in graphite form is more stable than carbide form. During cooling if it is subjected to a controlled cooling rate and adequate alloying addition then carbon gets precipitated out as graphite flakes. It has high Si content because it promotes the formation of graphite during solidification. Gray cast irons have negligible ductility but are useful because they can be easily casted to complex shapes and are inexpensive. These also have very low impact resistance.

2. **White cast iron:**

Rapid solidification of gray iron results in white cast iron. It has white fracture surface. Graphite flakes are not present in this type of cast irons rather; an iron carbide network is present that gives a white fracture surface. The Si content is lower to minimize the graphitizing effect. They are hard and have excellent abrasion resistance. But they also have excessive brittleness and poor machinability. To enhance wear resistance generally Mo, Cr, Ni are added to it.

3. **Mottled iron:**

This type of cast iron is not intentionally produced and results from a transition between gray and white cast irons. It is not necessarily a desirable material.

4. **Malleable cast iron:**

It is produced by heat treatment of white cast iron in which the iron carbide network decomposes or breaks down into *temper carbon*. This process is called malleablization which involves two stages of annealing as the first stage of annealing and the second stage of annealing. Because of the absence of hard and brittle carbide phase, iron becomes malleable. Disadvantage of this type of cast iron is its limited section thickness and prolonged annealing cycles.

5. Spheroidal graphite cast iron or ductile iron:

It is produced by adopting special alloy addition and proper cooling rates so that the carbon can be converted to spherical forms which can be used in those fields where carbon in flake form or temper form can't be used. The nodules are formed during solidification and not during heat treatment. It can be of three types namely, ferritic, pearlitic/ferritic, martensitic. It has excellent mechanical properties which can be compared to steels.

There is a subclass of ductile iron named as **Austempered ductile iron**. It has the same nodular or spherical graphite as in ductile iron but the matrix is a combination of bainite and stabilized austenite. Austempering is necessary to get this type of cast iron structure. Here graphite is present in compact form and shape of graphite is controlled by minor alloying addition. Austemperd ductile irons have excellent mechanical properties such has tensile strength, ductility and wear resistance.[2][3][14]

TYPES OF SG IRON

Depending upon the matrix phases, SG iron can be classified into four groups.

1. Ferritic
2. Pearlitic
3. Martensitic
4. Austentic

SG irons are generally ferritic type. But low yield strength and high ductility makes it difficult to be used in certain applications. Thus if some carbon is left intentionally in cementite form, property gets enhanced. Such type of SG iron is referred as pearlitic SG iron. If the rate of cooling is very high then the matrix will get converted into martensite. Due to its ductile nature it has limited applications. Thus the matrix may vary from a soft ductile ferritic structure through a hard and higher strength pearlitic structure to an austentic structure.[1]

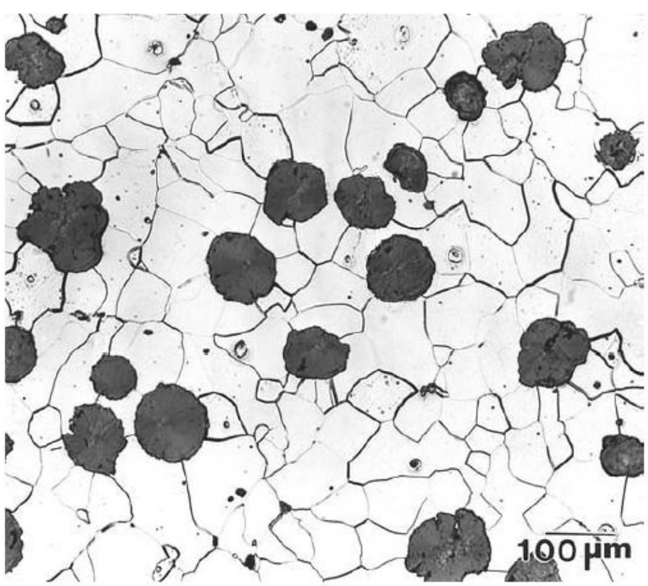

Figure 2.1: Ferritic ductile iron microstructure(Ref 3)

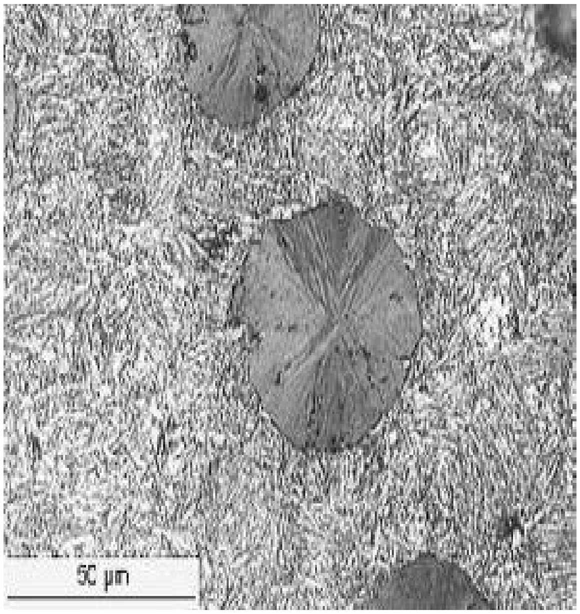

Figure 2.2: Pearlitic ductile iron microstructure(Ref 3)

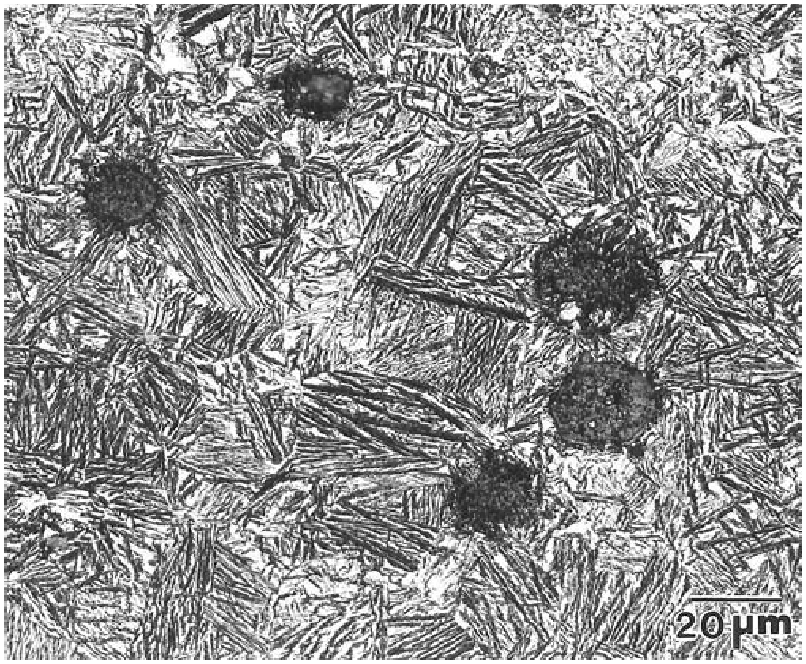

Figure 2.3: Austemperd ductile iron microstructure(Ref 3)

2.2 AVERAGE COMPOSITION OF SG IRON

ELEMENTS	CONTENT (Wt %)
Carbon	3.0-4.0
Silicon	1.8-2.8
Manganese	0.1-1.0
Phosphorus	0.01-1.0
Sulphur	0.01-0.03

Table 2.1: Average composition of SG iron

2.3 PRODUCTION OF SG IRON

1. **<u>Desulphurisation:</u>** Sulphur helps in the growth of graphite flakes. Thus while producing SG iron the raw materials should have low sulphur content (<0.1%). Sulphur should be removed during melting or by addition of a desulphurising agent like calcium carbide or soda ash.
2. **<u>Nodulising:</u>** Magnesium is added to the bath to tie up sulphur and oxygen and radically change the graphite growth morphology. Magnesium reacts with oxygen to form highly stable MgO which floats on the surface and can be skimmed off easily. Oxygen content thus reduces from typical levels of 90-135ppm to about 15-35ppm. Magnesium also reacts with sulphur to produce less stable MgS. Due to low solubility of magnesium in the metal and due to its volatile nature, reaction can become reversible if losses are not taken care of. Si is added for additional deoxidation. Group 1A, 2A, 3B elements can also be added for tying up sulphur and oxygen. Cerium forms highly stable oxides with S and

O and is less volatile than Mg. Addition of Mg is done when the melt is at 1500^0C but Mg vaporizes at 1100^0C. Magnesium being lighter floats on the bath and being reactive burn off at the surface. Hence it is generally added as Ni-Mg, Ni-Si-Mg alloy or magnesium coke to reduce the violence of the chemical reaction and to have saving in Mg. Thus magnesium addition plays an important role in the manufacture of SG iron. After nodulising treatment inoculants like Mg have their spherodising effect on the graphite structure so that graphite nodules can be formed.

3. **<u>Inoculation:</u>** The inoculation of cast iron involves the addition of small amounts of a material (inoculants) to the molten metal either just before or during pouring. Inoculation increases the number of points available for the precipitation and subsequent growth of graphite. This effect is often described as increasing the degree of nucleation of the iron. It can be seen that high levels promote graphite structure whilst low levels can result in the formation of either mottled structure or white irons. The need for a high level of nucleation increases as cooling rate increases, i.e. section size decreases. In addition to its effect on graphite morphology, magnesium is a powerful carbide promoter and as a result, compared with the gray irons, there is a far greater tendency for ductile irons to solidify with white or mottled structure. The primary purpose of inoculating ductile irons is to suppress formation of chill and mottle. In addition, inoculation is important in maintaining good nodule shape and also high nodule numbers. Graphite is not effective inoculants for ductile irons and all effective inoculants are based on silicon. The most widely used is foundry grade ferrosilicon, containing about 75% silicon. This alloy must contain small amounts of aluminum and calcium, in order to be fully effective; the amounts required are about 1.5-2.05 aluminum and about 0.3-1.0%. The inoculating

effect produced initially increases as the amount of inoculants is increased, but the effect soon begins to level off. A situation is reached where the extra inoculating benefit obtained is too small to justify for the increased addition. Usually, suppliers recommend smaller additions of the proprietary inoculants to achieve the same degree of nucleation. This partly compensates for their increased cost and has the advantage of decreasing the amount of silicon added.

4. **Solidification of SG iron:** Solidification of SG iron is always associated with proper under cooling. Graphite nuclei grow slowly and then are surrounded by austenite. The combination of austenite and graphite corresponds to the eutectic point at eutectic temperature. Austenite which gets supersaturated with carbon cools and a new equilibrium is established at the graphite/austenite interface. The excess of carbon diffuses towards the graphite nodule where it precipitates out.[1][7]

CHAPTER 3: PROPERTIES & APPLICATION OF SG IRON

3.1 PROPERTIES OF SG IRON

We take into account the mechanical properties, physical properties and service properties while we consider any material to be used for industrial applications. While mechanical properties takes into account tensile strength, hardness, elongation, proof stress, elastic modulus, impact and fatigue strength, physical properties include damping capacity, conductivity and machinability. The material to be used should be able to survive under the service conditions which can be determined by its wear resistance, heat resistance and corrosion resistance.[5]

Properties:

- **Tensile strength:** Ductile iron has higher tensile strength generally ranging from 414Mpa for ferritic grades to 1380Mpa for martensitic or austempered ductile iron grades.
- **Yield strength:** It is the stress at which the materials begins to have plastic deformation. For ductile irons generally 0.2% offset yield strength is calculated. Yield strength of ductile iron ranges from 275Mpa for ferritic grades to 620Mpa for martensitic grades.
- **Ductility:** Ductile irons have considerable ductility. Elongation can sometimes as high as 25% which is applicable for lower grades only. Austempered ductile irons have the best combination of strength and ductility.

- **Modulus of elasticity:** Ductile irons show a proportional stress-strain limit which looks similar to that of steels but is hampered by plastic deformation. The modulus of elasticity of ductile varies from 162-170Gpa.
- **Easy to cast :** High fluidity enables it to be easily casted.
- **Excellent corrosion resistance:** Ductile irons have very good corrosion resistance property.
- **Machinability:** Has a very good machinabilty due the graphite which is available in free form. Thus chip formation is easier.
- **Cost per unit strength:** It is lower than most of the materials. Thus has wide range of applications for which it can be used.[5][6][7]

3.2 EFFECT OF ALLOYING ELEMENTS ON PROPERTIES OF SG IRON

1). **Silicon:** [7] As the Si in the ductile iron matrix provides the ferritic matrix with the pearlitic structure. Silicon enhances the performance of ductile iron at elevated temperature by stabilizing the ferritic matrix and forming the silicon reach surface layer, which inhibits the oxidation.

The potentially objectionable influences of increasing silicon content are:

i). Reduced impact test energy.

ii). Increased impact transition temperature.

iii). Decreased thermal conductivity.

Si is used to promote ferrite and to strengthen ferrite. So Si is generally held below 2.2% when producing the ferritic grades and between 2.5% and 2.8% when producing pearlitic grades

2). **Manganese:** As it is a mild pearlite promoter, with some required properties like proof stress and hardness to a small extent. As Mn retards the onset of the eutectoid transformation, decreases the rate of diffusion of C in ferrite and stabilize cementite (Fe_3C).But the problem here is the embrittlement caused by it, so the limiting range would be 0.3-1.0.

3). **Copper:** It is a strong pearlite promoter. It increases the proof stress with also the tensile strength and hardness with no embrittlement in matrix. So in the pearlitic grade of the ductile iron the copper is kept between 0.4-0.8% and is a contaminant in the ferritic grade.

4). **Nickel:** As it helps in increasing the U.T.S without affecting the impact values .So it can be in the range of 0.5-2.0. It strengthens ferrite, but has much less effect than Silicon in reducing ductility. But there is the danger of embrittlement with the large additions; in excess of 2%.Due to the high cost it is generally present as traces in the matrix.

5). **Molybdenum:** It is a mild pearlite promoter. It Forms intercellular carbides especially in heavy sections. Increases proof stress and hardness. There is danger of embrittlement, giving low tensile strength and ductility. It also improves elevated temperature properties.

6). **Chromium:** As it prevents the corrosion by forming the layer of chromium oxide on the surface and stops the further exposition of the surface to the atmosphere. But as it is a strong carbide former so not required in carbide free structure .

8).**Sulphur and Phosphorus:** As 'P' is kept intentionally very low, as it is not required because it causes cold shortness and so the property of ductile iron will be ruined. But the addition of S is done for better machinability, but it is kept around 0.009 and maximum 0.015%.As the larger additions of Sulphur may cause the hot (red) shortness.[7][1]

3.3 APPLICATION OF SG IRON

Much of the annual production of ductile iron is in the form of ductile iron pipe, used for water and sewer lines. Ductile iron pipe is stronger and easier to tap, requires less support and provides greater flow area compared with pipe made from other materials. In difficult terrain it can be a better choice than PVC, concrete, polyethylene, or steel pipe.

Ductile iron is specifically useful in many automotive components, where strength needs surpass that of aluminum but do not necessarily require steel. Other major industrial applications include off-highway diesel trucks, class 8 trucks, agricultural tractors, and oil well pumps. [2]

Since ductile irons have properties similar to steels their application has been extended to

- **Caskets in Nuclear Industry**
- **Tractor life arm.**
- **Check beam for lifting track.**
- **Mine cage guide brackets.**
- **Gear wheel and pinion blanks and brake drum.**
- **Machines worm steel.**
- **Flywheel.**
- **Thrust bearing.**
- **Frame for high speed diesel engine.**
- **Four throw crankshaft.**
- **Fully machined piston for large marine diesel engine.**
- **Bevel wheel.**
- **Hydraulic clutch on diesel engine for heavy vehicle.**
- **Fittings overhead electric transmission lines.**

CHAPTER 4: HEAT TREATMENTS

To fully utilize the range of properties beyond the limits of those produced in as-cast condition; Heat treatment is a very valuable tool. The heat Treatments can be carried out on Spheroidal Graphite Iron to achieve the following:[15]

1. increase toughness and ductility,
2. increase strength and wear resistance,
3. increase corrosion resistance,
4. stabilize the microstructure, to minimize growth,
5. equalize properties in castings with widely varying section sizes,
6. improve consistency of properties,
7. improve machinability, and
8. Relieve internal stresses.

The following heat treatments were employed for our study:

1. Austenitizing
2. Tempering
3. Austempering

4.1 Austenitizing

It is the heat treatment process in which the ferrous alloy is held above the upper critical temperature for a sufficiently long time to ensure that the matrix has fully transformed to austenite. Austenitizing is done before any heat treatment process to produce a uniform matrix. [15]

4.2 Tempering

It is the heat treatment process in which the quench-hardened or normalized ferrous alloy is reheated to a temperature below the transformation temperature and cooling is done at any desired rate. Tempering is done to relieve thermal residual stresses and for improving ductility & toughness. The enhancement in ductility by tempering leads to depreciation in the hardness & strength.[16]

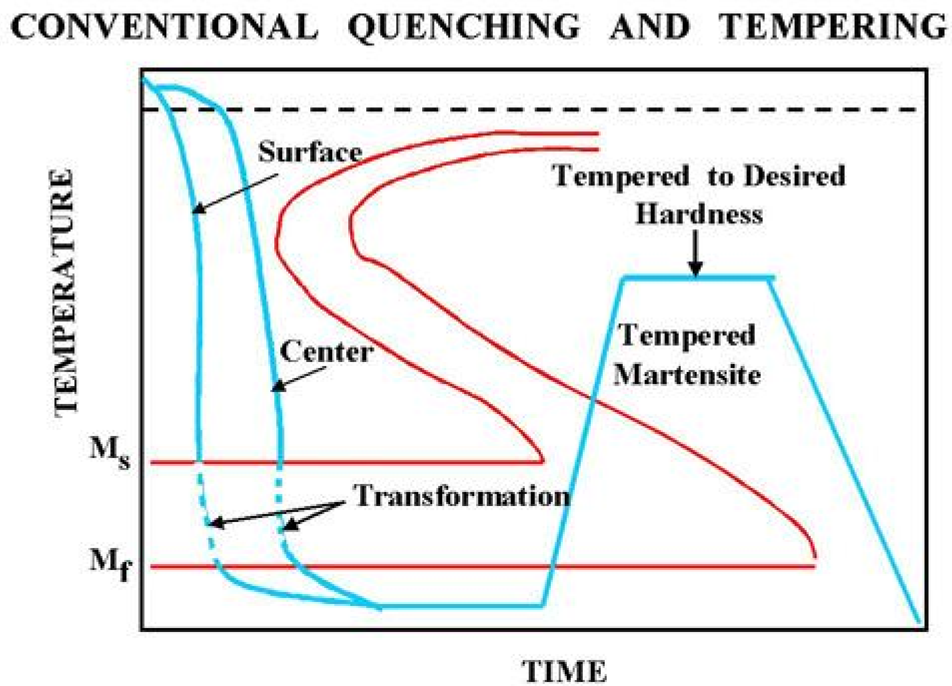

Figure 4.1: Conventional Quench & Tempering Process(Ref:21)
(http://info.lu.farmingdale.edu/depts/met/met205/tempering.html)

Tempering results in:

1. Reduced brittleness
2. Enhanced ductility & Toughness
3. Reduced Hardness & Strength

4.3 Austempering

It is the heat treatment process in which the ferrous alloy is first quenched from temperature higher than upper critical temperature, in a medium allowing a high rate of heat abstraction to prevent high-temperature transformation products, to a temperature where holding leads to 100% bainite formation.[16]

The figure below show the TTT diagram for the Autempering process.

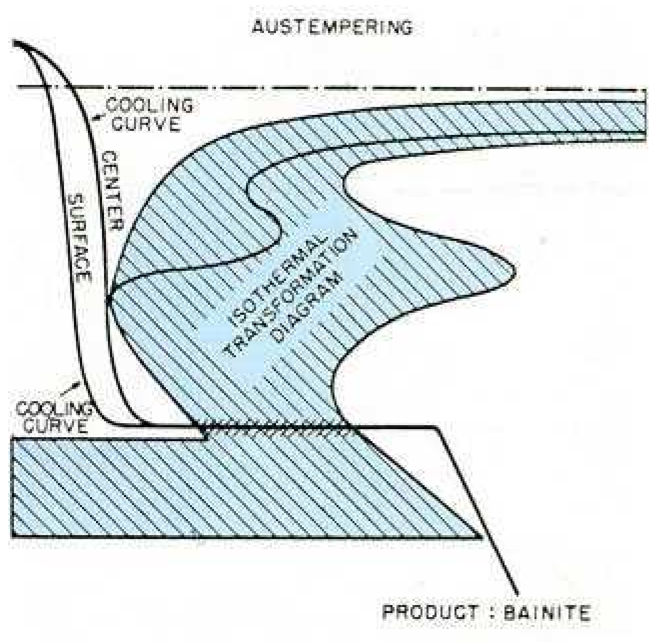

Figure 4.2: Austempering TTT Diagram(Ref:19)

In Austempering there is nucleation & growth of acicular ferrite within the austenite and the carbon is rejected to the austenite. The resulting microstructure is termed as ausferrite. [17]

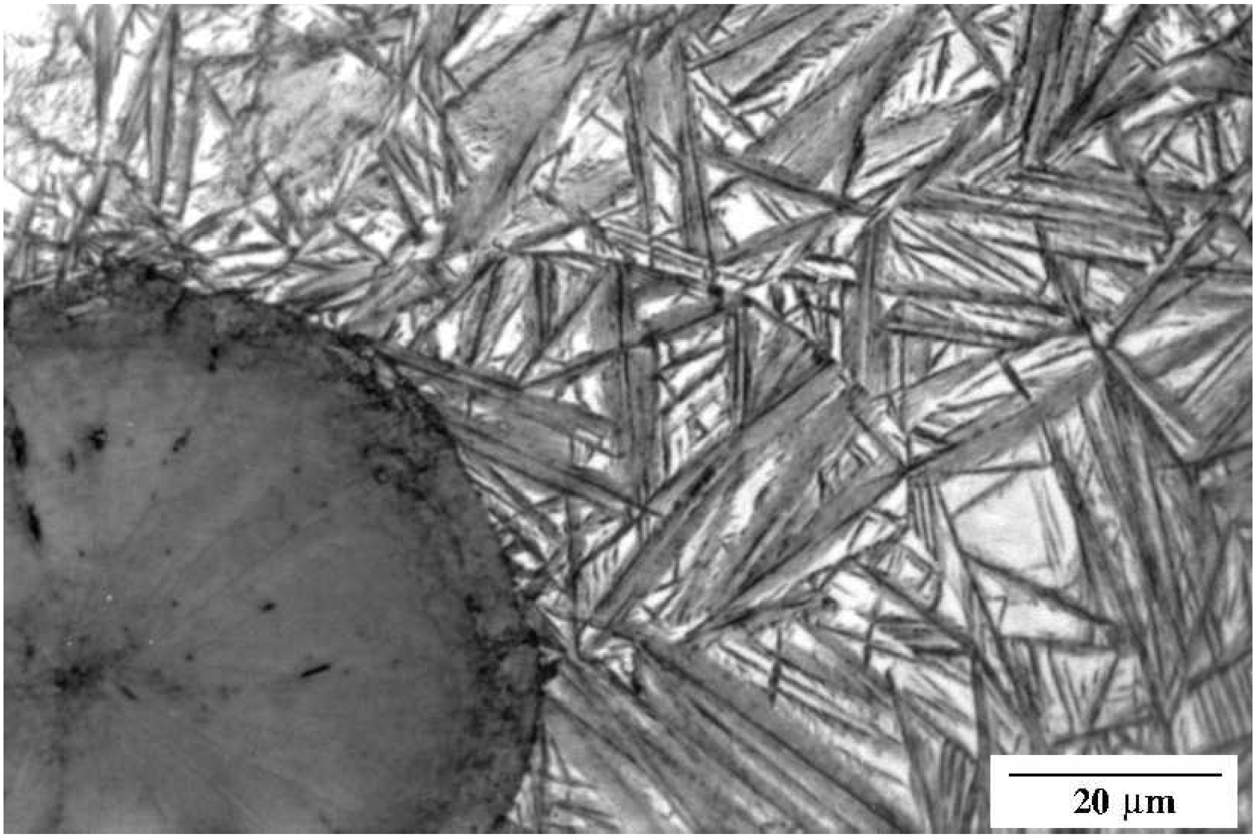

Figure 4.3: Austempered Ductile Iron microstructure produced by Austenitising at 950 Deg. C and austempered at 350 Deg. C for 63min.(Ref: 18)

Austempering results in: [16]

1. Enhanced ductility
2. Enhanced toughness
3. Higher Hardness
4. Lesser distortion & Quench cracks than observed after tempering.

CHAPTER 5: EXPERIMENTAL PROCEDURE

The various stages that were carried out are:

1. Specimen Preparation
2. Heat Treatments
3. Mechanical Property Study

5.1 Specimen Preparation

The specimen in as-cast condition had the following composition:

Specimen:	X_A	X_B
C	**3.62%**	**3.58%**
Si	**2.14%**	**2.08%**
Mn	**0.18%**	**0.20%**
S	**0.009%**	**0.042%**
P	**0.026%**	**0.024%**
Cr	**0.029%**	**0.03%**
Ni	**0.72%**	**0.10%**
Cu	**0.02%**	**0.43%**

Table 5.1: Composition of Specimens used for Testing

The two types of specimen were cut into 10 pieces each of a specific size according to ASTM standards.

According to ASTM Standards (ASTM E8) the ratio of gauge diameter to gauge length should be 1:5. Hence turning was done to get the required specifications:

1. Gauge Length: 70mm
2. Gauge Diameter: 14mm
3. Total Length: 90mm
4. Grip Diameter: 20mm

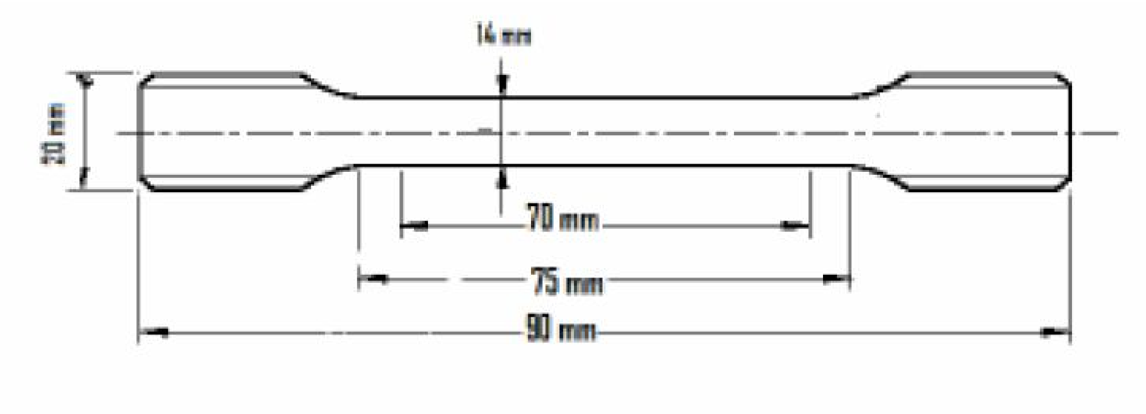

Figure 5.1: Specimen Specifications

5.2 Heat Treatments:

The various heat-treatments employed for our study were:

1. Austenitizing, Quench & Tempering
2. Austempering

Austenitizing, Quench & Tempering

1. Three specimens of each type were heated to austenitize at 900 Deg C for 2 hours.

2. These austenitized specimens were quenched in an oil bath maintained at room temperature.
3. These specimens were now put inside the furnace maintained at 600 Deg. C and then were taken out of the furnace one by one for air-cooling after duration of 30min, 1hr 30min & 2hrs.

Austempering

1. Six specimen of each type were heated to austenitize at 900 Deg. C for 2 hours.
2. Three specimens of each type were then immediately transferred to the salt bath, which was prepared by taking 50% $NaNO_3$ and 50% KNO_3 salt mixture, maintained at 300 Deg. C.
3. The remaining three specimen of each type were transferred to the other salt bath of same composition maintained at 350 Deg. C
4. One by one specimen of each type in pairs was taken out of the salt baths at 300 Deg. C & 350 Deg. C. after a duration 1hr 15min, 2hr, 2hr 30min

5.3 Study of Mechanical Properties

5.3.1 Hardness Testing

The method utilized for hardness testing was Rockwell Hardness Testing. In this process

1. The specimen was put on the specimen holder
2. The minor load of 10kg was applied by rotating the axle
3. When the reading on the display became zero the rotating was stopped and final loading was applied by pressing the loading button.
4. The scale used was A-scale.

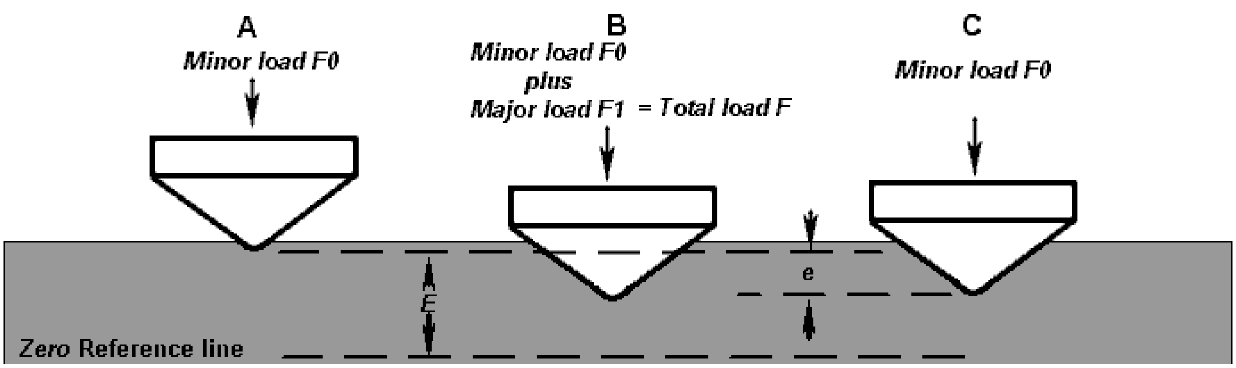

Figure 5.2: **Rockwell Principle** (Ref:22)

Rockwell Hardness = E-e [22]

5.3.2 Tensile Testing

ASTM A536 method (EN1563) was employed for tensile testing. The machine used was Instron Universal Testing Machine Model 1195.

The specimen prepared in the specimen preparation stage was made according to ASTM A536 specification and hence was directly used.

The process is as followed:

1. The specimen's dimensions(thickness/gauge length/total length in mm etc) were measured accurately with a electronic slide calipers
2. The details were fed into the testing machine
3. The distance between the jaws was fixed according to the gauge length of the specimen
4. The specimen was inserted into the machine and gripped by the jaws.
5. Maximum load was set to 150KN and loading was done till the specimen failed.
6. The corresponding readings generated for Yield Stength, %elongation & Ultimate Tensile Strength was noted.

5.3.3 Impact Testing

Charpy V-notch test described in ASTM E23 was employed for impact testing. In this method the specimen was shaped as shown in the figure below:[23]

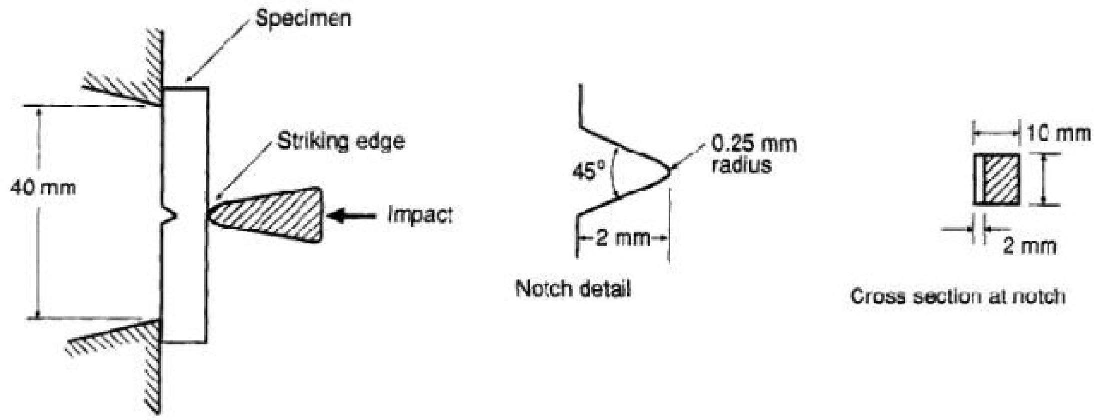

Figure 5.3: Charpy V-Notch Impact Testing Specimen Measurements(Ref:23)

The process used is as follows: [25]

1. The Charpy specimen was placed horizontally across supports with the notch away from the hammer.
2. The indicator pointer was slided to the left until it indicated the maximum energy range on the upper Charpy-Tension scale.
3. The pendulum arm was raised to the right until it is firmly supported by the latching mechanism.
4. The pendulum was released by pushing up on the release knob. The hammer dropped, striking the specimen, with a swing through dependent on the amount of energy absorbed by the test specimen. The indicator moved and stopped when peak swing through was registered, providing a direct reading of the energy absorbed by the specimen.[25]
5. The indicated value from the Charpy scale read and recorded.

CHAPTER 6: RESULTS & DISCUSSIONS

6.1 HARDNESS TESTING RESULTS

Specimen Specification	Specimen	Time	Hardness (R_A)
As Received	A	--	44
	B	--	45
Quenched from 900 and tempered at 600 degree Celsius	A	30min	60
		1hr	59
		2hr	59
	B	30min	61
		1hr	60
		2hr	59
Austempered at 300 degree Celsius	A	1hr15min	67
		2hr	63
		2hr30min	64
	B	1hr15min	63
		2hr	66
		2hr30min	67
Austempered at 350 degree Celsius	A	1hr 15min	48
		2hr	53
		2hr 30min	54
	B	1hr 15min	49
		2hr	50
		2hr 30min	50

Table 6.1: Rockwell Hardness (A-Scale) of various heat treated S.G. Cast Iron Specimens

6.2 Tensile Testing

Specimen Specification	Specimen	Time	UTS (in MPa)	Yield Strength (in MPa)	Elongation %
As Received	A	--	370	285	22
	B	--	565	215	8
Quenched from 900 deg C and tempered at 600 degree Celsius	A	30min	376	290	24
		1hr	372	296	26.3
		2hr	369	287	27.4
	B	30min	575	228	10.1
		1hr	570	223	11.4
		2hr	568	217	13
Austempered at 300 degree Celsius	A	1hr15min	510	305	23
		2hr	520	312	24.5
		2hr30min	512	322	23.5
	B	1hr15min	830	245	9
		2hr	847	256	9.7
		2hr30min	839	269	9.3
Austempered at 350 degree Celsius	A	1hr 15min	450	339	25
		2hr	456	348	26
		2hr 30min	462	362	25.7
	B	1hr 15min	690	279	10
		2hr	706	284	11.2
		2hr 30min	695	298	10.3

Table 6.2: Tensile Properties of various heat treated S.G. Cast Iron Specimens

6.3 IMPACT TESTING:

Specimen Specification	Specimen	Time	Charpy Impact (J)
As Received	A	--	17.66
	B	--	7.66
Quenched from 900 and tempered at 600 degree Celsius	A	30min	16.67
		1hr	15.67
		2hr	14.67
	B	30min	6.67
		1hr	5.67
		2hr	4.67
Austempered at 300 degree Celsius	A	1hr 15min	12.67
		2hr	11.67
		2hr 30min	10.67
	B	1hr 15min	4.67
		2hr	3.67
		2hr 30min	3.67
Austempered at 350 degree Celsius	A	1hr 15min	9.67
		2hr	8.67
		2hr 30min	6.67
	B	1hr 15min	3
		2hr	2.67
		2hr 30min	2.67

Table 6.3: Impact Properties of various heat treated S.G. Cast Iron Specimens

6.4 PLOTS & DISCUSSIONS:

Hardness Testing:

According to the results obtained the following tabulation and graphs have been plotted for various heat-treatments conducted:

Specimen A	Hardness (R_A)
As Cast Sample	44
Austenitizing, Quenchigng & Tempering at 600 Deg. C for 2hrs	59
Austempering at 300 Deg. C. for 2hr	63
Austempering at 350 Deg. C for 2hr	53

Table 6.4: Hardness Testing Tabulation for as-Cast & Heat-treated Specimens for type A

Specimen B	Hardness (R_A)
As Cast Sample	45
Austenitizing, Quenchigng & Tempering at 600 Deg. C for 2hrs	59
Austempering at 300 Deg. C. for 2hr	66
Austempering at 350 Deg. C for 2hr	50

Table 6.5: Hardness Testing Tabulation for as-Cast & Heat-treated Specimens for type B

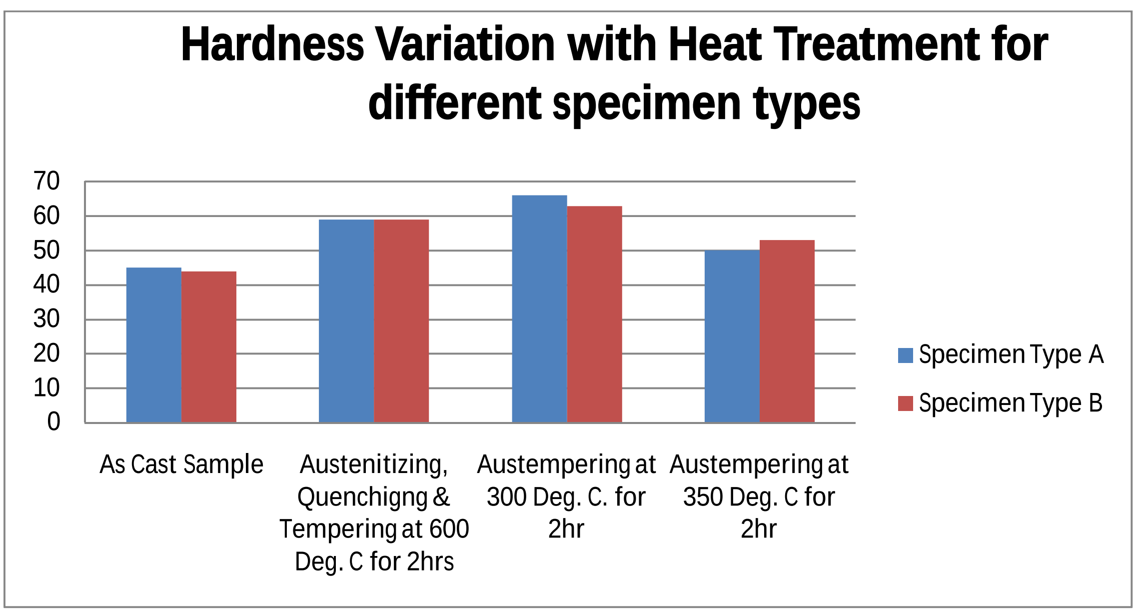

Figure 6.1:Hardness variation with heat treatment for different specimen types

OBSERVATION 1:

It can be observed from the hardness data obtained that when tempering time was increased from 30 minutes to 2 hours hardness values decreased. This was same for both samples having Copper and Nickel respectively.

INFERENCE 1:

As tempering time increases hardness decreases and softness is induced in the quenched specimen.

OBSERVATION 2:

It has been observed that as the Austempering temperature increases hardness value decreases. As the Austempering temperature increases from 300^0C to 350^0C the hardness values decreases for the time intervals of 1 hour, 2 hour and 2.30 hours. However, the hardness values increases as the Austempering time is increased from 1hour 15 minutes to 2hours 30 minutes.

INFERENCE 2:

It is quite clear from the hardness data that as the Austempering time increased, hardness value increases due the presence of ferrite and high carbon austenite. As temperature increases this high carbon austenite decomposes to ferrite and cementite thus decreasing the hardness. Hence with increase in Austempering temperature, hardness decreases. We can clearly see that in case of Austempering hardness is maximum at 2hour and 30minutes. Hardness value is lowest at 1hour 30minutes time.

Note: Among all the heat treatment operations we have the highest hardness in case of Austempering at 300^0C followed by tempering at 600^0C and then Austempering at 350^0C

Tensile Testing:

Tempering:

Specimen	Time	UTS (in MPa)	Yield Strength (in MPa)	Ductility (%)
A	30min	376	290	24
	1hr	372	296	26.3
	2hr	369	287	27.4
B	30min	575	228	10.1
	1hr	570	223	11.4
	2hr	568	217	13

Table 6.6: Tensile Testing Tabulation for Specimens tempered at 600 Deg. C

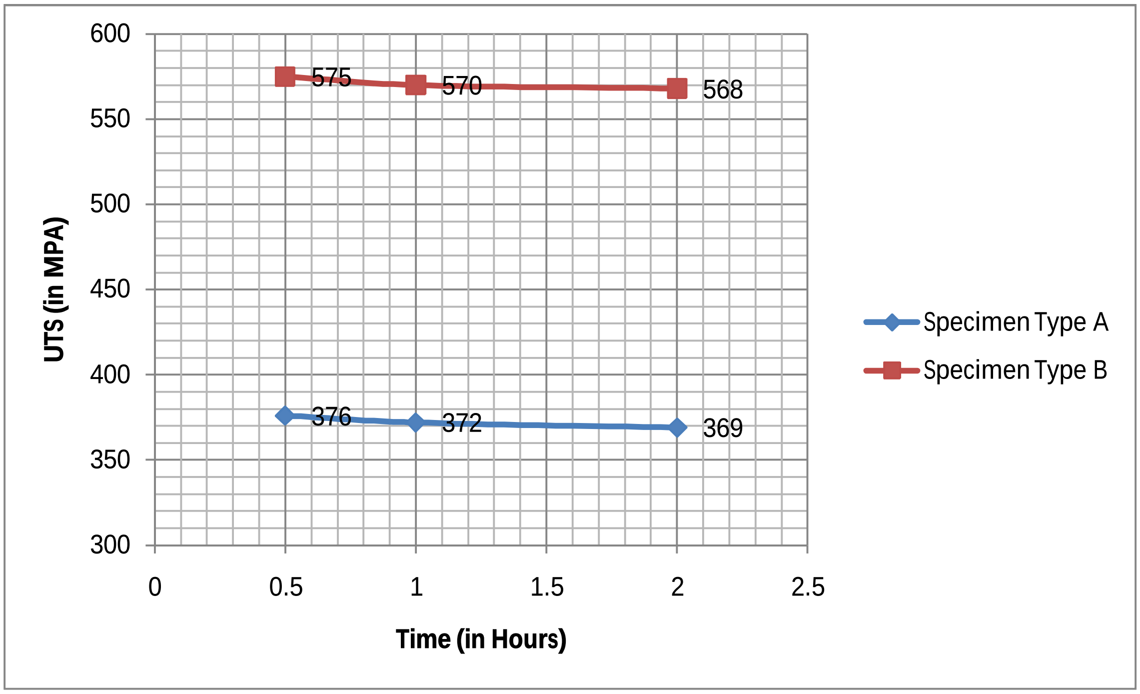

Figure 6.2: UTS vs Time plot for Tempering

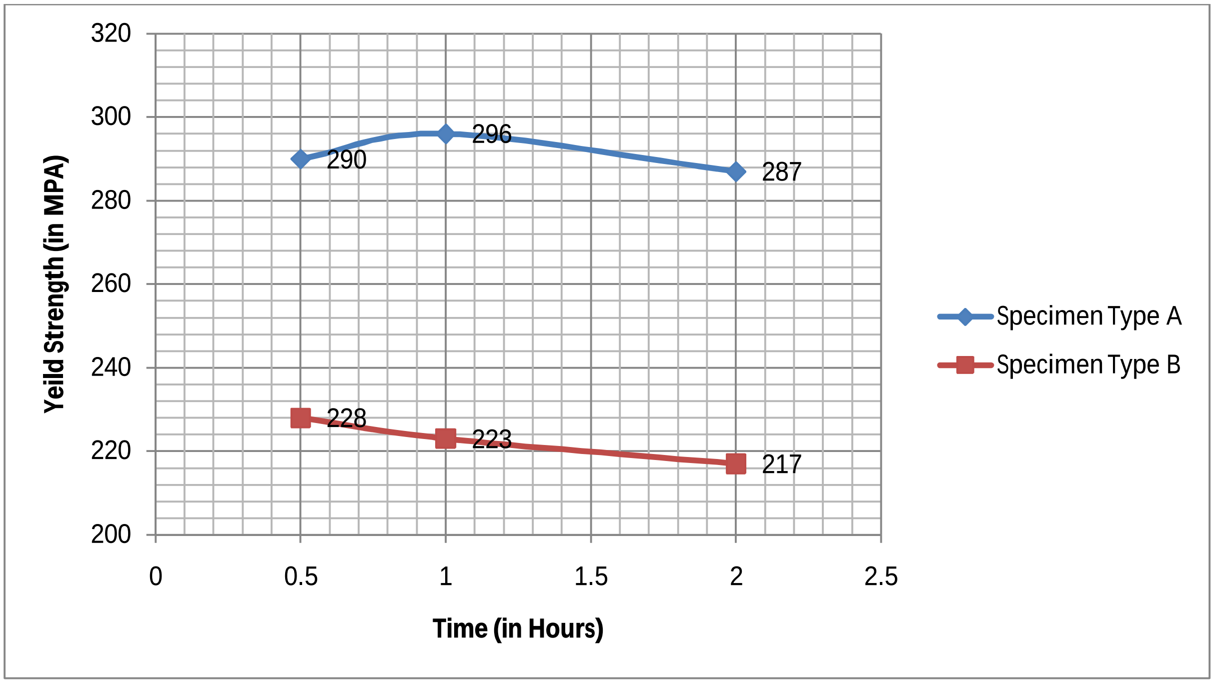

Figure 6.3: Yield strength vs Time plot for Tempering

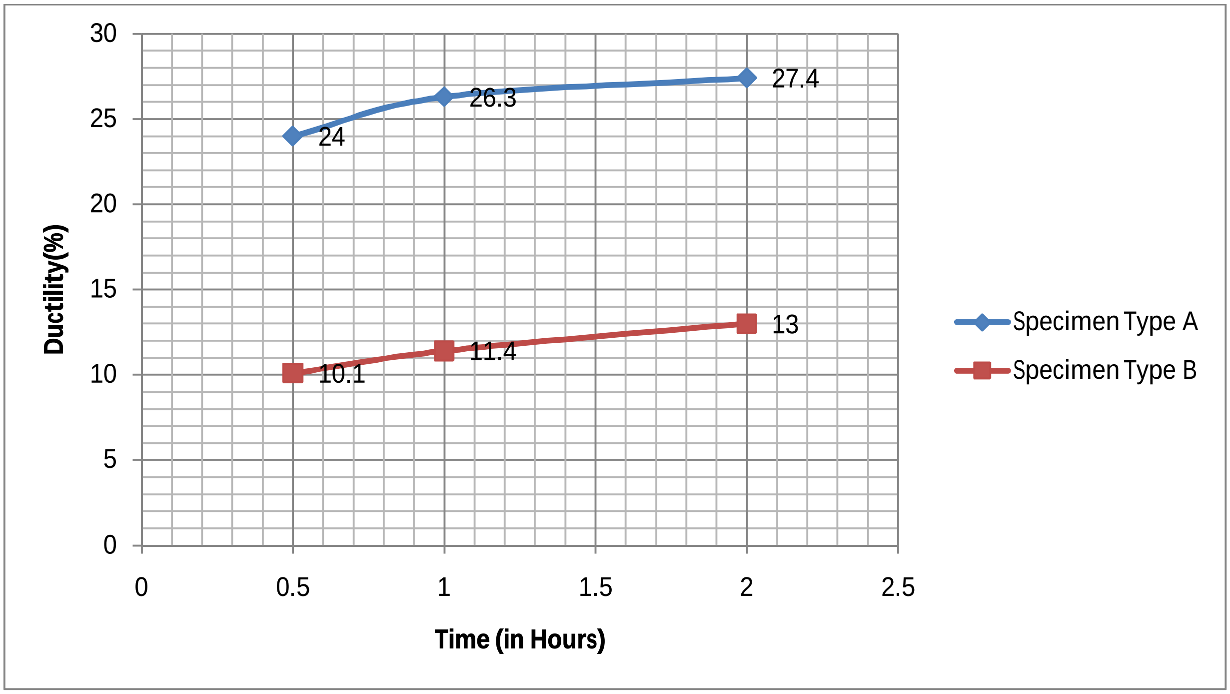

Figure 6.4: Ductility vs Time plot for Tempering

OBSERVATION 3:

It has been observed from the graphs that with tempering temperature remaining constant, as we increase the tempering time both UTS decreases gradually while yield strength first increases, then decreases. It was observed that with increase in tempering time ductility increases clearly showing tempering effect.

INFERENCE 3:

As the tempering time is increased UTS decreases gradually while yield strength shows an abnormal behavior. Yield strength first increases, then decreases as time is increased further. This may be due the formation of lower and upper banite. As time increases the high carbon austenite decomposes into carbide and ferrite. Carbide is detrimental to mechanical properties of the material. Thus UTS and yield strength decreases.

Austempering at 300 Deg. C.

Specimen	Time	UTS (in MPa)	Yield Strength (in MPa)	Ductility (%)
A	1hr15min	510	305	23
	2hr	520	312	24.5
	2hr30min	512	322	23.5
B	1hr15min	830	245	9
	2hr	847	256	9.7
	2hr30min	839	269	9.3

Table 6.7: Tensile Testing Tabulation for Specimens austempered at 300 Deg. C

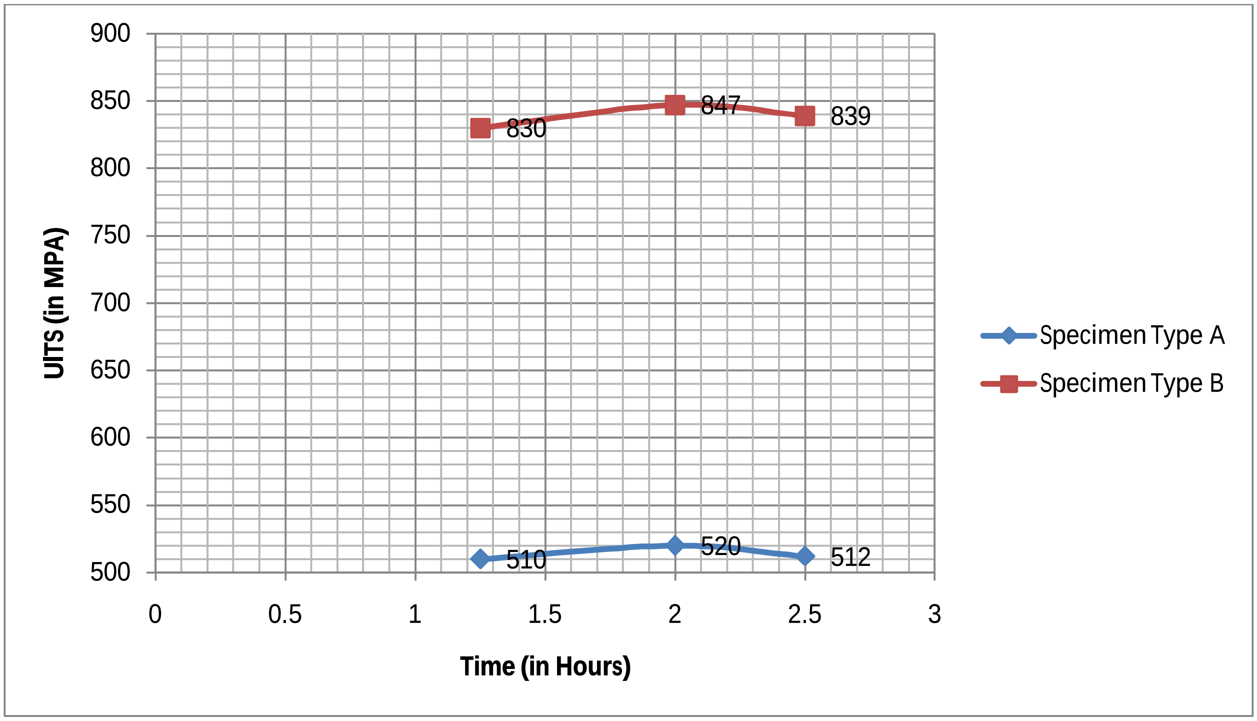

Figure 6.5: UTS vs Time plot for Austempering at 300deg C

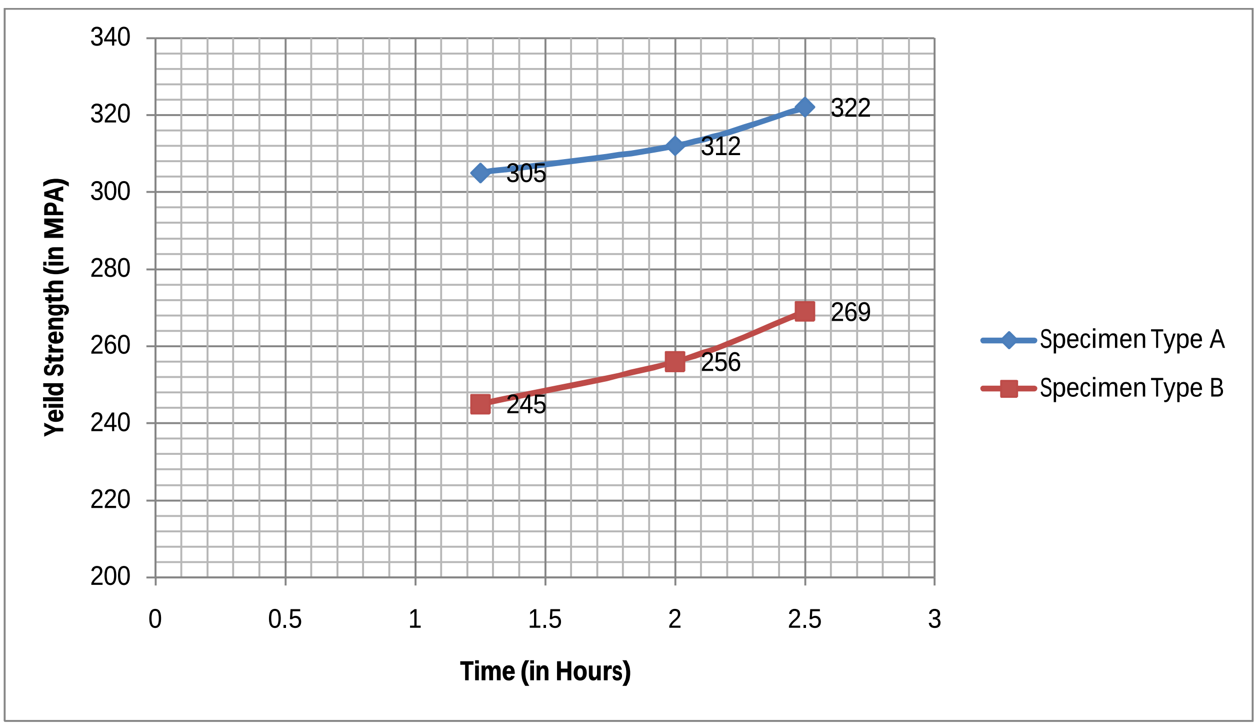

Figure 6.6: Yield strength vs Time plot for Austempering at 300deg C

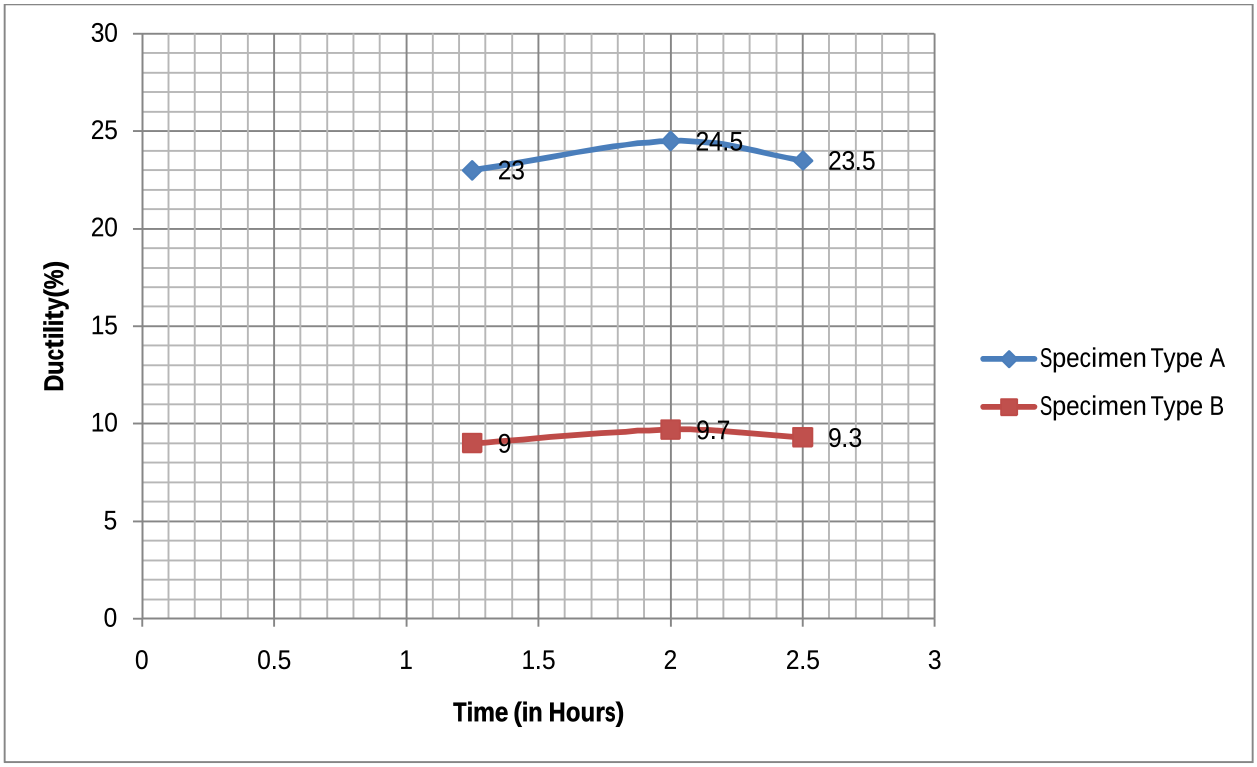

Figure 6.7: Ductility vs Time plot for Austempering at 300 deg C

Austempering at 350 Deg. C.

Specimen	Time	UTS (in MPa)	Yield Strength (in MPa)	Ductility (%)
A	1hr 15min	450	339	25
	2hr	456	348	26
	2hr 30min	462	362	25.7
B	1hr 15min	690	279	10
	2hr	706	284	11.2
	2hr 30min	695	298	10.3

Table 6.8: Tensile Testing Tabulation for Specimens austempered at 350 Deg. C

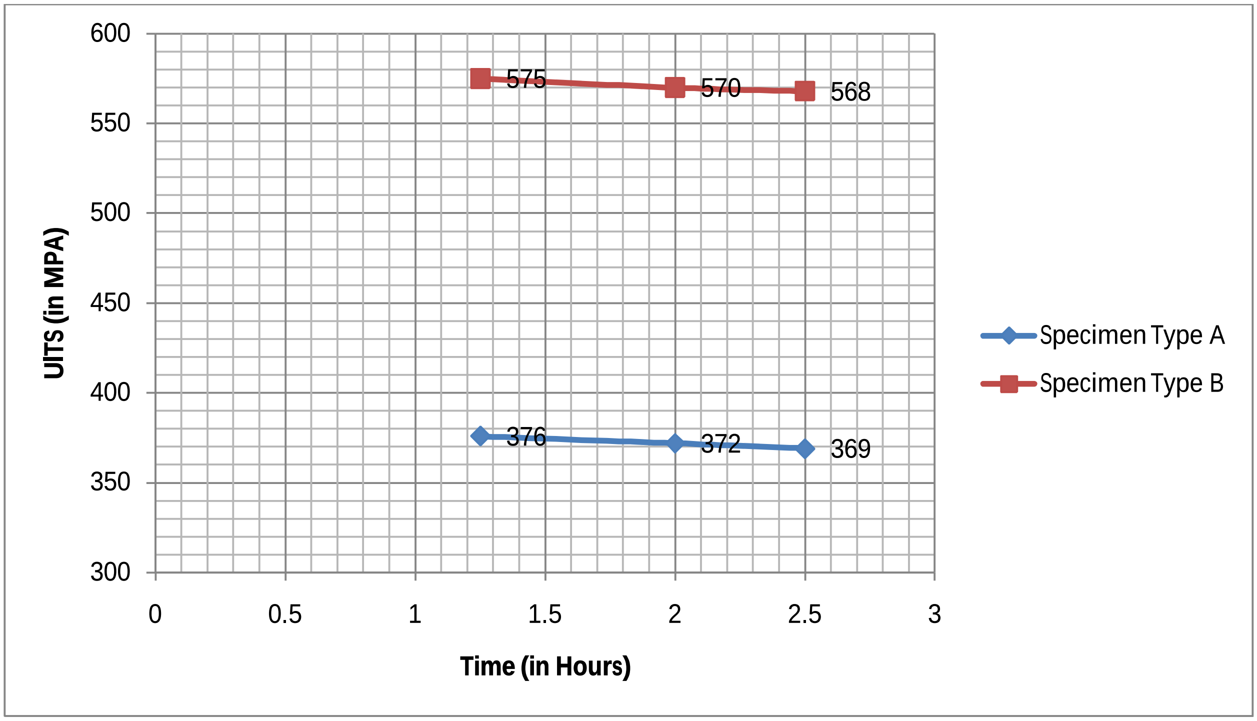

Figure 6.8: UTS vs Time plot for Austempering at 300 deg C

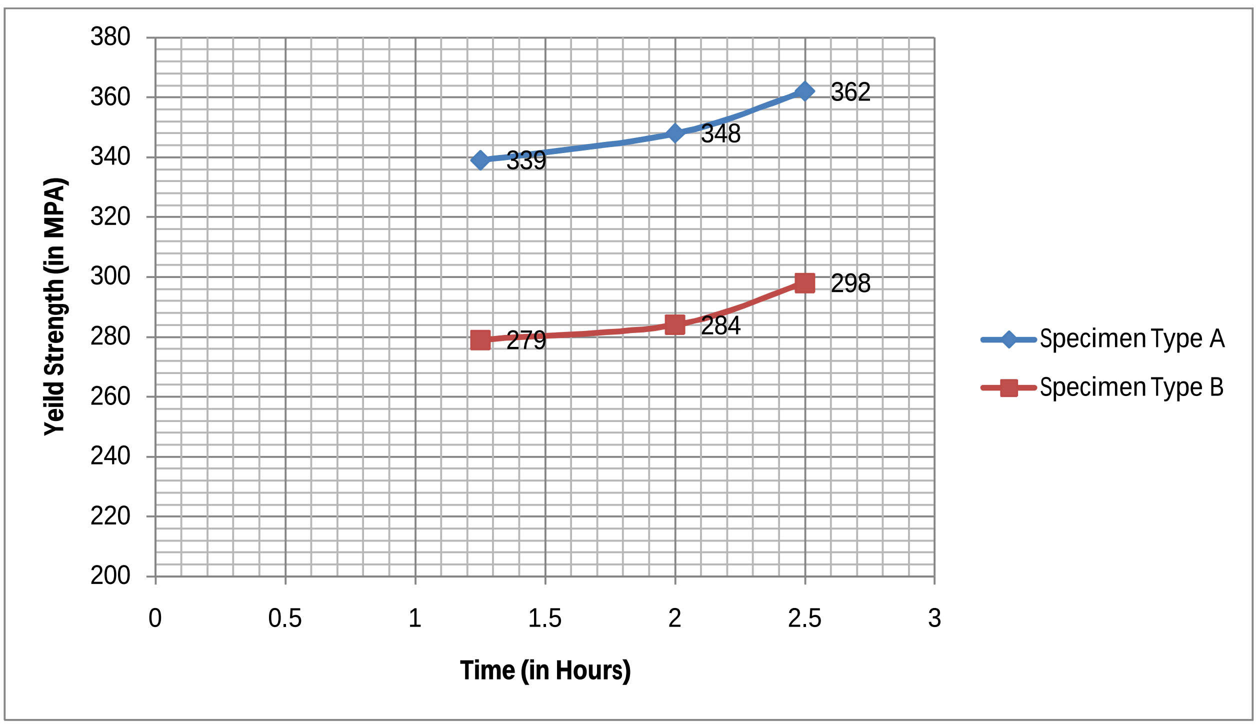

Figure 6.9: Yield strength vs Time plot for Austempering at 350deg C

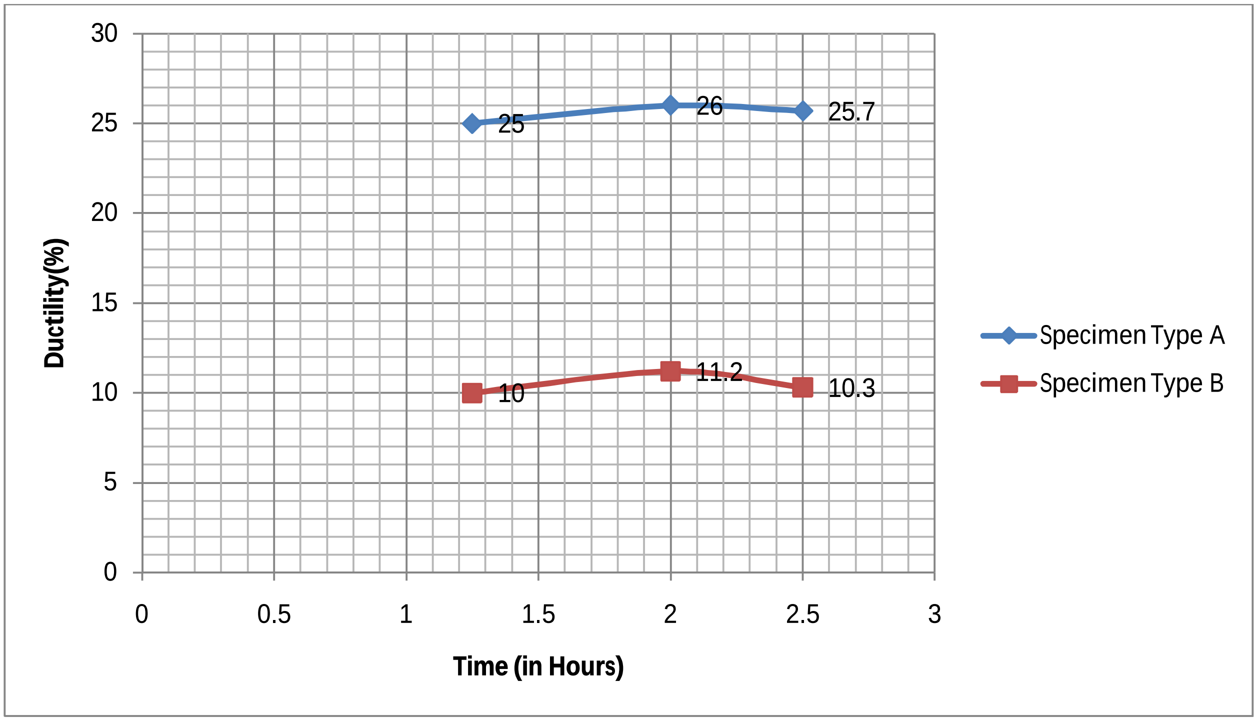

Figure 6.10: Ductility vs Time plot for Austempering at 350deg C

Mechanical Properties for Specimen A(C: 3.62%, Si: 2.14%, Mn: 0.18%, S: 0.009%, P: 0.026%, Cr: 0.029%, Ni: 0.72%, Cu: 0.02%):

Specimen A	Time	UTS (in MPa)	Yield Strength (in MPa)	Ductility (%)
As-Cast Sample	---	370	285	22
Austenitizing, Quenchigng & Tempering at 600 Deg. C	2hr	369	287	27.4
Austempering 300 Deg. C	2hr	520	312	24.5
Austempering at 350 Deg. C	2hr	456	348	26

Table 6.9 : Tensile Testing Tabulation for as-Cast & Heat-treated Specimens for type A

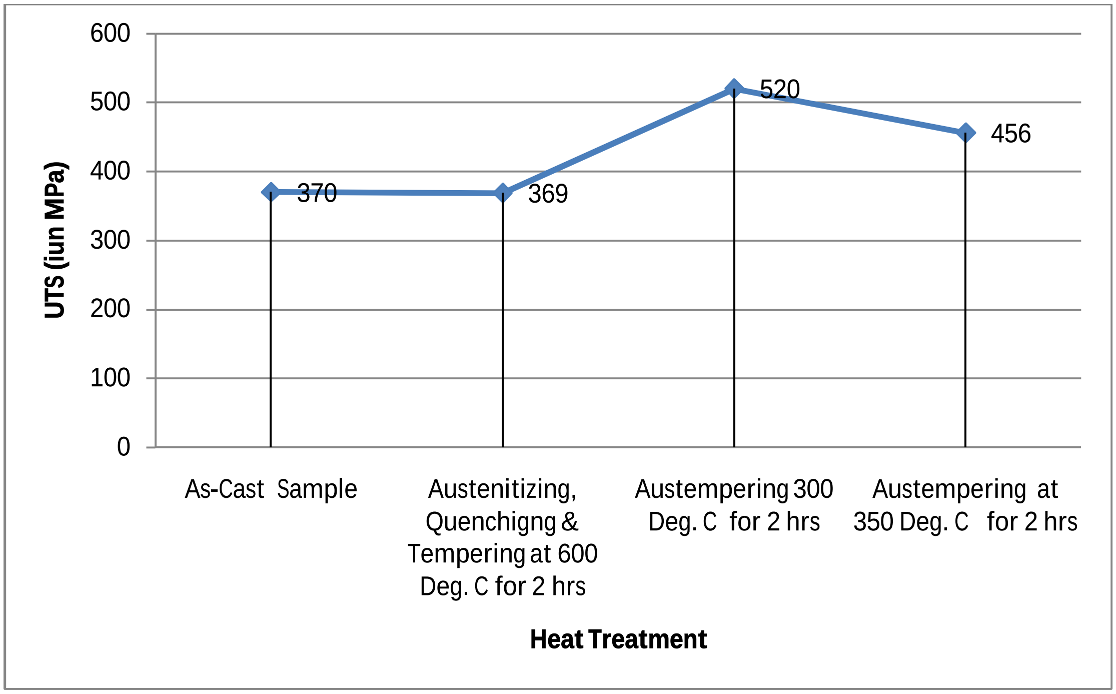

Figure 6.11: UTS vs Heat treatment plot for specimen A

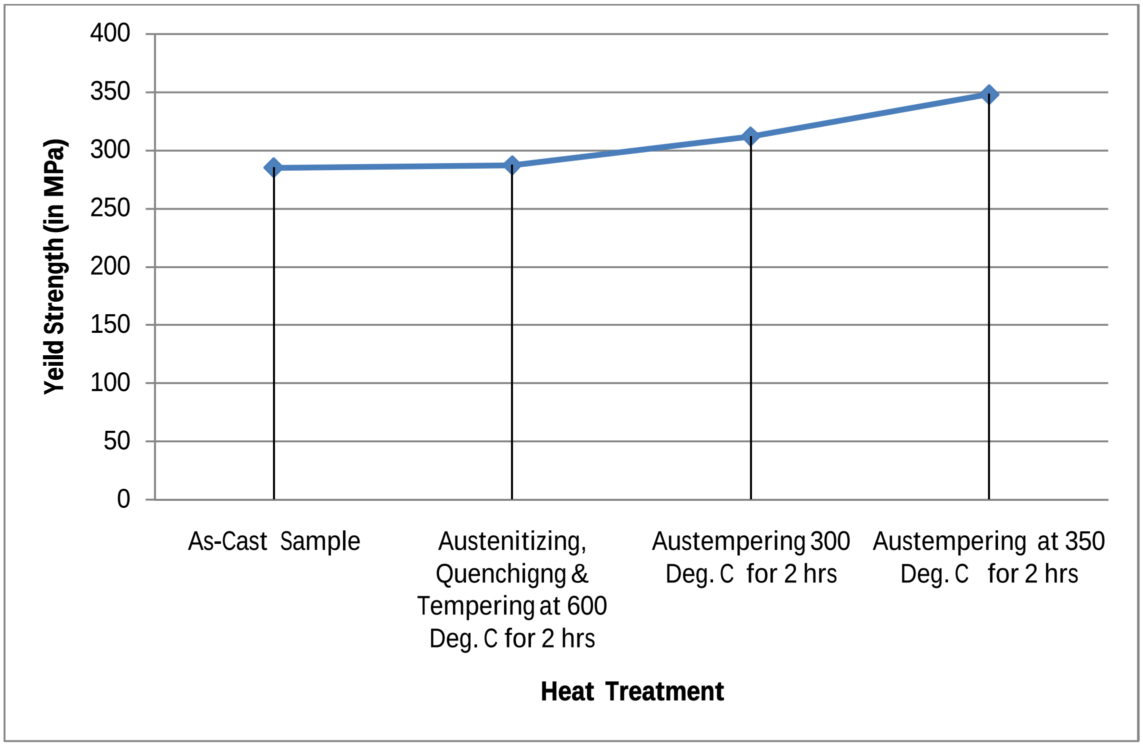

Figure 6.12: Yield Strength vs Heat treatment plot for specimen A

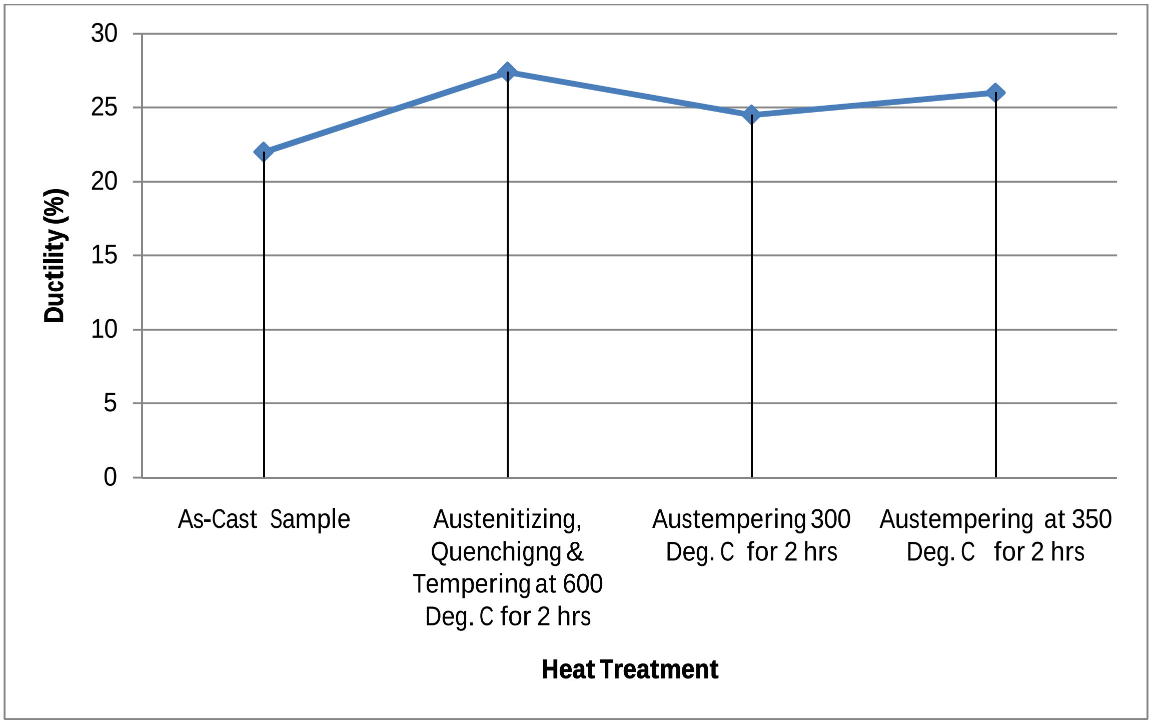

Figure 6.13: Ductility vs Heat treatment plot for specimen A

Mechanical Properties for Specimen B(C: 3.58%, Si: 2.08%, Mn: 0.2%, S: 0.042%, P: 0.024%, Cr: 0.03%, Ni: 0.1%, Cu: 0.43%):

Specimen B	Time	UTS (in MPa)	Yield Strength (in MPa)	Ductility (%)
As Cast Sample	--	565	215	8
Austenitizing, Quenchigng & Tempering at 600 Deg. C	2hr	568	217	13
Austempering at 300 Deg. C.	2hr	847	256	9.7
Austempering at 350 Deg. C	2hr	706	284	11.2

Table 6.10: Tensile Testing Tabulation for as-Cast & Heat-treated Specimens for type B

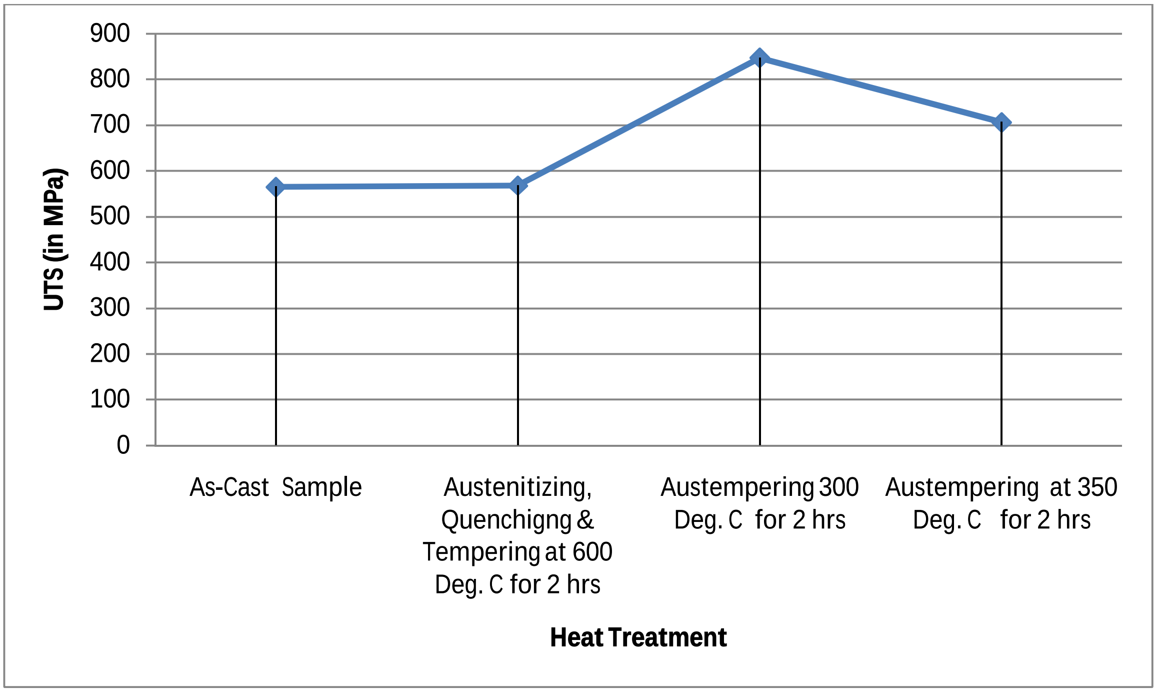

Figure 6.14: UTS vs Heat treatment plot for specimen B

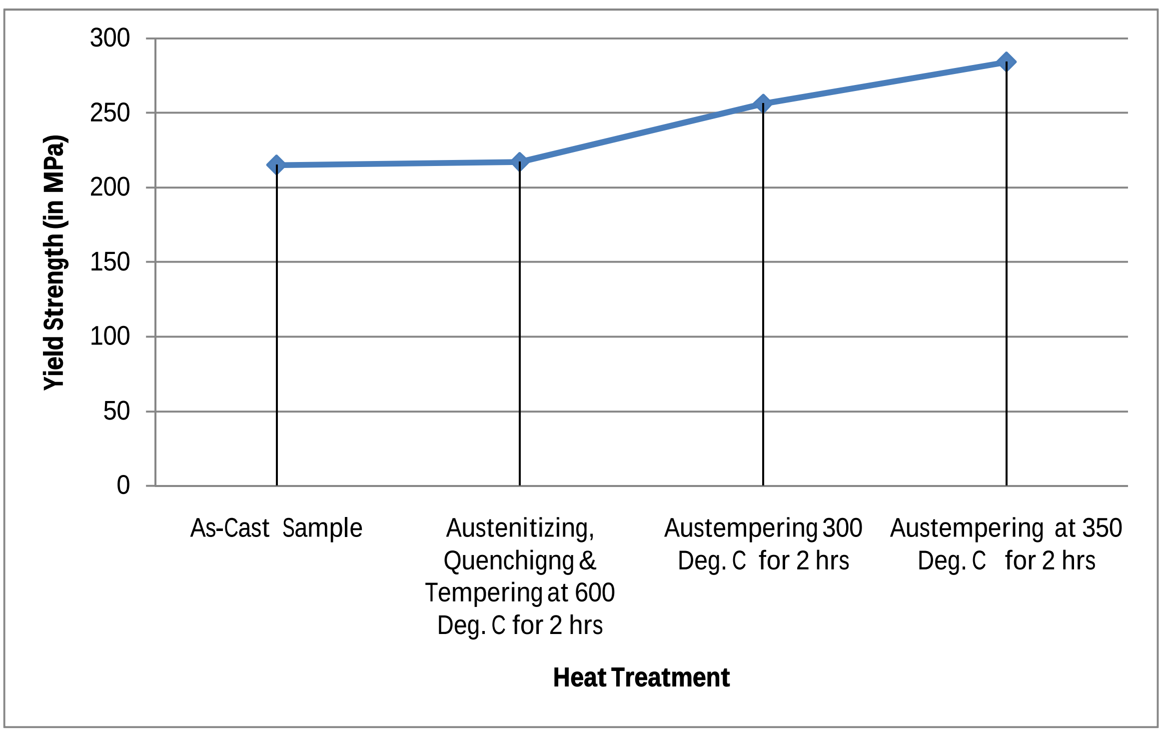

Figure 6.15: Yield Strength vs Heat treatment plot for specimen B

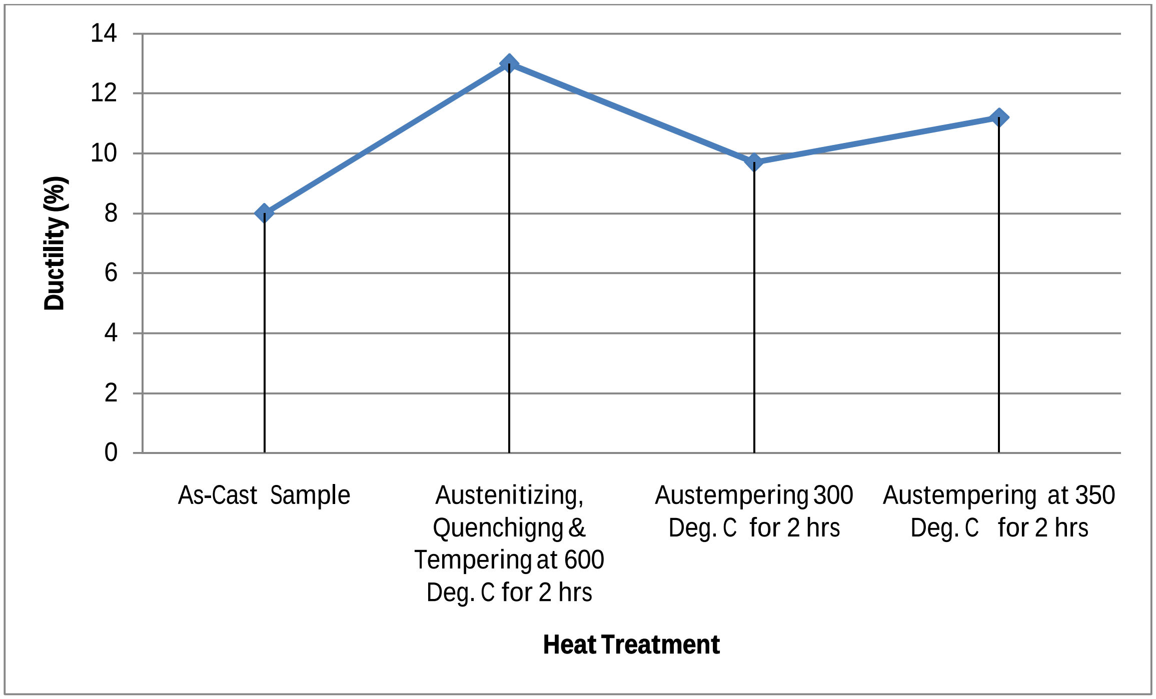

Figure 6.16: Ductility vs Heat treatment plot for specimen B

OBSERVATION 4:

From the tabulations we can clearly see that, as we increase the Austempering temperature from 300 to 350^{0}C there is a gradual decrease in UTS values. The yield strength though increases with temperature. Ductility first increases then decreases when Austempering time is increased. It increases when Austempering temperature is increased.

INFERENCE 4:

UTS decreases as Austempering temperature increases while it first increases then decreases when time is increased. Yield strength first increases and then decreases with increase in time while it increases as the Austempering temperature is increased. Ductility increases with increase in Austempering temperature and shows a abnormal behavior with increase in Austempering time.

IMPACT TESTING:

OBSERVATION 5:

From the tabulations it is clear that the impact values decrease slightly with increase in tempering time from 30minutes to 2hours. In case of austempering impact values also decrease slightly when the temperature is changed from 300^0C to 350^0C

INFERENCE 5:

Hence it can be inferred that as the time is increased from 30minutes to 2 hours for tempering (at 600^0C) & from 1hour 15minutes to 2hour 30minutes for austempering (at 300^0C and 350^0C) process the impact values decreases slightly. Hence Heat treatment processes like austempering & tempering though enhance mechanical properties but lead to decrease in impact values.

CHAPTER 7: CONCLUSION

From the results obtained it can be concluded that the properties of Spheroidal Graphite Cast Iron can be enhanced & altered according to service condition & application requirement. Earlier limitations on the usage of ductile iron due to limited knowledge of property enhancement processes can now be overcome by various heat treatment operations. It has been found that by heat-operations like tempering & austempering, their brittle behavior can be transformed to ductile behavior applicable in various applications. These heat-treatment processes produce properties comparable to steels at a very low cost. Tempering significantly increases ductility, also applications where higher hardness is desired low temperature tempering operation can be applied but that will hamper the strength requirements. But comparing all the heat treatment processes austempering gives the best combination of yield strength, UTS & % elongation as well as hardness. Hence it can be considered to be the best possible heat treatment operation that can be applied to ductile iron.

CHAPTER 8: REFERENCES

1. James H Davidson, Microstructure of steel and cast irons, New York, Springer-verlag, 2003, ISBN 3-540-20963-8, Part 3, chapter 21, page 356-363
2. AVNER Sidney H ,Introduction to Physical Metallurgy, Second Edition, MCGRAW-HILL INTERNATIONAL EDITIONS, chapter 11, page 450-453
3. B.L. Bramfitt and A.O. Ben scoter, Metallographer's Guide: Practices and Procedures for Irons and Steels, USA, 2002, ASM International, Chapter 1, page 16-21
4. Hafiz M, Material science and engg : A, 15 January 2003, Elsevier, Volume 340, PP 1-7
5. http://www.ductile.org/didata/Section3/3part1.htm.
6. http://www.ductile.org/didata/Section3/3part2.htm
7. MUHAMMAD ASHRAF SHEIKH, *Effects of heat treatment and alloying elements on characteristics of austempered ductile iron*, Lahore, Department of Metallurgical & Materials Engineering, University of Engineering and Technology Lahore, 2008.
8. http://eprints.hec.gov.pk/2798/1/88S.htm
9. http://www.wikipedia.org
10. http://www.asminternational.org/pdf/spotlights/6040_ch1.pdf
11. Vijendra Singh, Physical metallurgy, New Delhi, Reprint edition 2007, Standard Publishers, 2007
12. Miguel angel yescas- gonzalez and HKDH Bhadeshia, Cast irons
13. Elliot Roy, Cast iron Technology, UK, Butterworth-Heinemann Ltd, 1988
14. Handbook on design engineers digest on ductile iron, Eighth edition, IBM, West Germany,

15. *Ductile Iron Data for Design Engineers*. Retrieved May 5th, 2010, from Ductile Iron Society: http://www.ductile.org/didata/Section7/7intro.htm
16. AVNER Sidney H ,Introduction to Physical Metallurgy, Second Edition, MCGRAW-HILL INTERNATIONAL EDITIONS Materials Science and Metallurgy Series, Chapter 8, Page:303-315,668,686 ISBN: 0-07-085018-6
17. http://www.advancedcast.com/austempering-process.htm
18. http://www.msm.cam.ac.uk/phase-trans/2001/adi/adimore.html
19. http://www.steel-heattreatment.com/Steel-Heat-Treatment.htm
20. **Rashidi Ali M. and Moshrefi-Torbati M.** Effect of tempering conditions on the mechanical properties of ductile cast iron with dual matrix structure (DMS), **Materials Letters,** Volume 45, Issues 3-4, September 2000, Pages 203-207, SCIENCE DIRECT http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TX9-41069G8-D&_user=1657113&_coverDate=09/30/2000&_alid=1321620334&_rdoc=1&_fmt=high&_orig=search&_cdi=5585&_sort=r&_docanchor=&view=c&_ct=1486&_acct=C000053917&_version=1&_urlVersion=0&_userid=1657113&md5=c3553a47b0ce58846a204b507109fbc8
21. http://info.lu.farmingdale.edu/depts/met/met205/tempering.html
22. http://www.gordonengland.co.uk/hardness/rockwell.htm
23. http://civilx.unm.edu/laboratories_ss/mechmat/charpy.html
24. J. Zimba, D. J. Simbi and E. Navara, Austempered ductile iron: an alternative material for earth moving components, Cement and Concrete Composites,Volume 25, Issue 6, August 2003, Pages 643-649 Infrastructure Development http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6TWF-47CH5G3-B&_user=1657113&_coverDate=08/31/2003&_alid=1323380774&_rdoc=13&_fmt=high&_orig=search&_cdi=5561&_sort=r&_docanchor=&view=c&_ct=14762&_acct=C000053917&_version=1&_urlVersion=0&_userid=1657113&md5=52f009b85824e72c6b41e2b3f83f733e
25. http://civilx.unm.edu/laboratories_ss/mechmat/305-Impact.doc
26. Dieter Goerge E., Mechanical Metallurgy, Adapted by David Bacon, McGraw-Hill Book Company, Materials Science & Metallurgy Series, SI Metric Edition, ISBN: 0-07-100406-8
27. http://www.ductile.org/didata/Section7/7intro.htm (HEAT TREATMENTS OF DUCTILE IRON)